

Propagation of Cylindrical strong shockwaves including the Effect of disturbance

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Abstract

The propagation of shock waves in a medium can be significantly influence by disturbances that exist behind the shock front. In the present work, the effects of such disturbances on the propagation of strong cylindrical shock waves are investigated.

A modified CCW (Chester-Chisnell-Whitham) method is employed to study the propagation of cylindrical shock waves through an ideal and rotating gas. The analysis is carried out for a permissible shock front location with an arbitrary initial density distribution of the form, $\rho_0 = \rho' \log(1 + \lambda r)$ where ρ' is the density at the axis of symmetry and λ is a non-dimensionalizing constant.

The numerical estimates of the flow variables are computed for those values of propagation distance r that are permitted by the entropy distribution condition.

The results obtained are presented through graphs and compared with those of earlier work.

Key words: Cylindrical shockwaves; Rotating gas; Shock propagation; Shock-front location.

Introduction

The propagation of shock waves through rotating gases has been extensively evaluated using various differential techniques. Fluid rotation typically introduces two primary phenomena: initial density distribution variations and Coriolis forces. For instance, CCW (Chester-Chisnell-Whitham)[1-3] analyzed these effects utilizing the method of characteristics. To understand the specific impact of initial density distribution on shock propagation, Chaturani[4] deployed the similarity method, which was later adapted into a modified similarity approach by Chaturani and Kumar[6-8]. Through these similarity solutions, the strength of overtaking waves was computed numerically. However, because this methodology depends on a series expansion in terms of the inverse square of the Mach number where lower values correspond to strong shocks the resulting insights remain valid exclusively within the strong shock regime. Compounding this research, Yadav[14] investigated the influence of the propagation of freely propagating strong cylindrical shock waves in a rotating gas, under the initial density distribution of the form $\rho_0 = \rho' \exp(\lambda r)$ where ρ' is the density at the axis of symmetry and λ is a non-dimensional constant, has been investigated previously. However, the reported results were not considered reliable because the restriction on the numerical estimation of the flow variables at permissible shock-front locations was not taken into account.

Yadav [15] later addressed this limitation by studying shock-wave propagation at permissible shock-front locations for the first time. He also investigated the effect of overtaking disturbances on freely propagating shock waves and modified the Chester–Chisnell–Whitham (CCW)[1-3] approximation to obtain an exact theory. His work demonstrated that when the strength of the overtaking disturbance is known, the CCW approximation can be modified to provide an exact solution.

In the present paper, the modified method proposed by Yadav [14] has been employed to investigate the effect of overtaking disturbances on the propagation of strong cylindrical shock waves in a rotating ideal gas. The initial density distribution is assumed to be $\rho_0 = \rho' \log(1 + \lambda r)$ where ρ' denotes the density at the axis of symmetry and λ is a non-dimensional constant. Analytical expressions for the shock velocity and shock strength, modified by overtaking disturbances, have been obtained.

The numerical estimation of the flow variables has been carried out only for those propagation distances r that satisfy the permissible initial density condition, $\rho_0 \propto \rho^\gamma$ where γ is the adiabatic index of the gas.

The results obtained here are depicted through graphs. Also the results have been compared with the earlier work by yadav[14].

Basic Equations, Boundary Condition and Characteristic Equations:

The equations governing the flow enclosed by the shock front are

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{v^2}{r} &= 0 \\ \left[\frac{\partial}{\partial t} + u \frac{\partial}{\partial r} \right] &= 0 \quad \dots (1) \\ \rho \left[\frac{\partial}{\partial t} + u \frac{\partial}{\partial r} \right] + \rho \left[\frac{\partial u}{\partial r} + \frac{u}{r} \right] &= 0 \\ \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} - a^2 \left[\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} \right] &= 0 \end{aligned}$$

Where u, v are the radial and azimuthal component of the Particle velocity and r is the radial co-ordinate. p, ρ and $a = (\frac{\gamma p}{\rho})^{1/2}$ denote respectively the pressure, the density and local sound velocity.

Let p_0 and ρ_0 represent the undistributed value of the pressure and density in front of the shock and u, p and ρ be the value of respective quantities at any point immediately after the passage of the shock, then the well known Rankine-Hugoniot condition permit us to express u, p and ρ in the terms of the undistributed value of these quantities by means of the equations–

$$\begin{aligned} p &= \rho_0 a_0^2 \left\{ \frac{2}{(\gamma+1)} M^2 - \frac{(\gamma-1)}{\gamma(\gamma+1)} \right\} \\ \rho &= \rho_0 \frac{(\gamma+1)M^2}{(\gamma-1)M^2+2} \quad \dots (2) \\ u &= \frac{2a_0}{(\gamma+1)} \left(M - \frac{1}{M} \right) \\ U &= a_0 M \end{aligned}$$

Where U is shock velocity and a_0 is the sound velocity in the undistributed medium and M Mach Number.

For strong shock $U \gg a_0$ then the boundary condition reduces to

$$\begin{aligned} p &= \frac{2\rho_0 U^2}{(\gamma+1)} \\ \rho &= \rho_0 \frac{(\gamma+1)}{(\gamma-1)} \quad \dots (3) \end{aligned}$$

$$u = \frac{2U}{(\gamma+1)}$$

The characteristic form of the system of flow equation (1) is obtained by forming appropriate linear combinations of the governing equations. This transformation yields equations in which the derivatives are taken along only one characteristic direction in the (r,t) plane.

For C+ disturbances, the corresponding characteristic equation can be written as follows

$$dp + \rho a du + \rho \frac{a^2}{(u+a)} \frac{dr}{r} - \rho \frac{av^2}{(u+a)} \frac{dr}{r} = 0 \quad \dots (4)$$

To estimate the strength of overtaking disturbances on independent C- characteristic is considered. The differential relation valid across C- disturbances is

$$dp - \rho a du + \rho \frac{av^2}{(u-a)} \frac{dr}{r} + \rho \frac{a^2 u}{(u-a)} \frac{dr}{r} = 0 \quad \dots (5)$$

Thus, Equations (4) and (5) represents the characteristic forms corresponding to the C+ and C- disturbances respectively. These equations are expressed in a form such that the derivatives are taken only along a single characteristic direction in the (r,t) plane.

Furthermore, as a consequence of the hydrostatic equation prevailing ahead of the shock front, we obtain

$$\frac{1}{\rho_0} \frac{dp_0}{dr} - \frac{v_0^2}{r} = 0 \quad \dots (6)$$

Now let us assume the initial density distribution to be the form i.e. an arbitrary form

$$\rho_0 = \rho' \log(1 + \lambda r) \quad \dots (7)$$

Substituting the value of ρ_0 into equation (6), it yields.

$$p_0 = \rho' \Omega_0^2 \lambda r^3 \left(\frac{1}{3} - \frac{\lambda r}{8} \right) + K_1 \quad \dots (8)$$

and

$$a_0 = a' \sqrt{\frac{k_1}{p'}} \left[1 + \frac{2}{\lambda r} + \frac{1}{3k_1} \rho' \Omega_0^2 r^2 + \frac{1}{24} \rho' \Omega_0^2 \lambda r^3 - \frac{1}{16k_1} \rho' \Omega_0^2 \lambda^2 r^4 \right] \quad \dots (9)$$

Where K_1 is constant of integration, represent the angular velocity of rotating gas.

$$dU^2 + \left[D_1 + \frac{B_1}{r} + E_1 r \right] U^2 dr - C_1 \Omega_0^2 dr = 0 \quad \dots (10)$$

Where

$$D_1 = \frac{\lambda}{2 \left[1 + \sqrt{\frac{\gamma}{2(\gamma-1)}} \right]}$$

$$B_1 = \frac{\left[1 + \gamma \left\{ 1 - \sqrt{\frac{\gamma(\gamma-1)}{2}} \right\} \right]}{2 \left[1 + \sqrt{\frac{\gamma}{2(\gamma-1)}} \right]}$$

$$E_1 = - \frac{\lambda^2}{2[1 + \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

$$C_1 = \frac{\frac{1(\gamma+1)^2}{4} \sqrt{2\gamma(\gamma-1)} [1 - \sqrt{\frac{\gamma(\gamma-1)}{2}}]}{2[1 + \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

Equation (10) can be simplified as

$$dU = [\frac{1}{2U} C_1 \Omega_0^2 r dr - (D_1 + \frac{B_1}{r} + E_1 r) \frac{U}{2} dr] \quad \dots (11)$$

For the C_+ disturbances generated by the shock, the increment in fluid velocity obtained using (3) and (11) can be expressed as

$$du_+ = \frac{2}{\gamma+1} [\frac{1}{2U} C_1 \Omega_0^2 r dr - (D_1 + \frac{B_1}{r} + E_1 r) \frac{U}{2} dr] \quad \dots (12)$$

Thus, to estimate the strength of the overtaking disturbances, an independent C_- characteristic is considered. Substituting the boundary condition (3) into Equation (5), we obtain

$$dU^2 + [D_2 + \frac{B_2}{r} + E_2 r] U^2 dr - C_2 \Omega_0^2 dr = 0 \quad \dots (13)$$

Where

$$D_2 = \frac{\lambda}{2[1 - \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

$$B_2 = \frac{[1 + \gamma \{1 - \sqrt{\frac{\gamma(\gamma-1)}{2}}\}]}{2[1 - \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

$$E_2 = - \frac{\lambda^2}{2[1 - \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

$$C_2 = \frac{\frac{1(\gamma+1)^2}{4} \sqrt{2\gamma(\gamma-1)} [1 + \sqrt{\frac{\gamma(\gamma-1)}{2}}]}{2[1 - \sqrt{\frac{\gamma}{2(\gamma-1)}}]}$$

Equation (13) can be simplified

$$dU = - [\frac{1}{2U} C_2 \Omega_0^2 r dr - (D_2 + \frac{B_2}{r} + E_2 r) \frac{U}{2} dr] \quad \dots (14)$$

For the C_- disturbances generated by the shock, the increment in fluid velocity obtained using (3) and (14) can be expressed as

$$du_- = - \frac{2}{\gamma+1} [\frac{1}{2U} C_2 \Omega_0^2 r dr + (D_2 + \frac{B_2}{r} + E_2 r) \frac{U}{2} dr] \quad \dots (15)$$

It determines the strength of the disturbances which overtake the shock. In presence of both C_+ and C_- disturbances the increment of the fluid velocity behind the shock will be related as

$$du_+ + du_- = 2 \frac{dU}{(\gamma+1)} \quad \dots (16)$$

Using equation (12) and (15), relation (16) gives

$$dU^2 + \left[D + \frac{B}{r} + Er \right] U^2 dr - (C_1 - C_2) \Omega_0^2 r dr = 0 \quad \dots (17)$$

Integration of equation (17)

$$U^2 = \frac{1}{2} C \Omega_0^2 r^2 + K_2 r^{-B} e^{\Delta_4} \quad \dots (18)$$

Where K_2 is a constant of integration, also remembering $\rho' \Omega_0^2 \lambda r^3 \left(\frac{1}{3} - \frac{\lambda r}{8} \right)$ should be less than 1 and

$$\Delta_4 = \frac{Er^2}{2} - Dr$$

and

$$D = \frac{D_1 + D_2}{2}, \quad B = \frac{B_1 + B_2}{2}, \quad C = \frac{C_1 + C_2}{2}, \quad E = \frac{E_1 + E_2}{2}$$

Now the expression for the pressure, the density and the particle velocity under the influences of overtaking disturbances for a strong case, can be written as

$$p = \frac{2\rho'}{(\gamma+1)} \left[\frac{1}{2} C \Omega_0^2 r^2 + k_2 r^{-B} e^{\Delta_4} \right] \log(1 + \lambda r)$$

$$\rho = \rho' \frac{(\gamma+1)}{(\gamma-1)} \log(1 + \lambda r) \quad \dots (19)$$

$$u = \frac{2}{(\gamma+1)} \left[\frac{1}{2} C \Omega_0^2 r^2 + k_2 r^{-B} e^{\Delta_4} \right]$$

Permissible shock front locations:

The pressure and density in the unperturbed state given by expression (7) and (8) must fulfill the initial entropy distribution condition, $p_0 \propto \rho^\gamma$ where γ is the adiabatic index of the gas. Substituting respective expression for p_0 and ρ_0 , we obtain

$$A_0 + A_1 r + A_2 r^2 + A_3 r^3 + A_4 r^4 + \dots = 0$$

Where

$$A_0 = K_1, \quad A_1 = -\gamma k \rho' \lambda, \quad A_2 = \frac{1}{2} \gamma k \rho' \gamma \lambda^2,$$

$$A_3 = \frac{1}{3} (\rho' \Omega_0^2 \lambda - \gamma k \rho' \gamma \lambda^3), \quad A_4 = \frac{1}{4} \left(\gamma k \rho' \gamma \lambda^4 - \frac{\rho' \Omega_0^4 \lambda^2}{2} \right)$$

This equation is expressed in increasing powers of the propagation distance r . In general, the number of roots is equal to the highest power of r . The roots evaluated for subsequent powers of r given in Table [1] below for $\rho' = 1.5$, $\lambda = 1$, $\Omega_0^2 = 2.0$ and $K_1 = 0.8$. This specific choice of p' and ρ' enables the evaluation of roots using Shridharacharya, Cardano and Descartes methods.

Table 1. Table for Permissible shock front locations

SNo.	Approximation	Value of Coefficient	Permissible Roots	Method Followed
For $\Omega_0^2 = 2.0$ and $K_1 = 0.8$				
1	$A_0 + A_1 r = 0$	$A_0 = 0.8$ $A_1 = -4.9592132$	0 and 0.1613159	Simple
2	$A_0 + A_1 r + A_2 r^2 = 0$	$A_2 = 2.4796066$	0, 1.8230238 and 0.1769762	Shridharacharya
3	$A_0 + A_1 r + A_2 r^2 + A_3 r^3 = 0$	$A_3 = -0.6530711$	0 and Two imaginary roots	Cardano
4	$A_0 + A_1 r + A_2 r^2 + A_3 r^3 + A_4 r^4 = 0$	$A_4 = 0.8648033$	0, 1.1680203, 0.1771856 and Two imaginary roots	Descarte

Table 2. Fulfillment of entropy distribution conditions in unperturbed state, for freely propagating strong cylindrical shock waves.

$$\rho' = 1.5, \quad p' = 14.1581, \quad \lambda = 1 \quad \text{and} \quad \gamma = 1.4$$

R	p_0	ρ_0	$p_0 \rho_0^{-\gamma}$	p_0	ρ_0	$p_0 \rho_0^{-\gamma}$
0.1613159	$\Omega_0^2 = 0.5, \quad K_1 = 1.62$			$\Omega_0^2 = 1.0, \quad K_1 = 1.39$		
	1.6209860	0.0974256	42.2315420	1.3919720	0.0974256	36.2747340
0.2010000	1.6218771	0.1193145	31.8161354	1.3937543	0.1193145	27.3731950
0.2410000	1.6231831	0.1406577	25.2894041	1.3963662	0.1406577	21.7555678
0.2820000	1.6250136	0.1618320	20.8049580	1.4000271	0.1618320	17.9244680
0.3210000	1.6272737	0.1813542	17.7632301	1.4045473	0.1813542	15.3319612
0.3610000	1.6301693	0.2007872	15.4391570	1.4103385	0.2007872	13.3503585
0.1613159	$\Omega_0^2 = 1.5, \quad k_1 = 1.62$			$\Omega_0^2 = 2.0, \quad k_1 = 0.8$		
	1.4295130	0.0974256	29.7779347	0.8039440	0.0944256	20.9451486
0.2010000	1.1456314	0.1193145	22.5000927	0.8075085	0.1193145	15.8593869
0.2410000	1.1495494	0.1406577	17.9101287	0.8127325	0.1406577	12.6624778
0.2820000	1.1550407	0.1618320	14.7879212	0.8200543	0.1618320	10.4991087
0.3210000	1.1618210	0.1813542	12.6823739	0.8290870	0.1813542	9.0503508
0.3610000	1.1705080	0.2007872	11.0801050	0.8406771	0.2007872	7.9579052

Table 3. "The Variation of Flow Variables in Propagating Cylindrical Strong Shockwaves"

$U/a_0 = 20, \quad \lambda = 1, \quad \rho' = 1.5, \quad p' = 14.1581, \quad \gamma = 1.4$
 $D = 0.6678675, \quad C = -4.5066661, \quad E = 0.6678675, \quad C_1 = -2.0160001$

R	U	U/a ₀	P	ρ	U
$\Omega_0^2 = 0.5, \quad k_1 = 1.62, \quad K_2 = 1.5182112^*$					
0.1613159	190.5540012	8.18057560	2948.003452	0.5845536	158.7950010
0.2010000	307.9327045	16.1809143	9428.087671	0.7158870	256.6105871
0.2410000	456.0178885	28.2260330	24375.07857	0.8439462	380.0149071
0.2820000	638.6030493	45.4266135	54997.77643	0.9709920	532.1692078
0.3210000	840.6835624	66.9224056	106809.8939	1.0881252	700.5696353
0.3610000	1075.152690	94.5900454	193691.6589	1.2047232	895.9605750
$\Omega_0^2 = 1.0, \quad k_1 = 1.39, \quad K_2 = 1.3032623^*$					
0.1613159	176.5499666	8.8330630	2530.621087	0.5845536	147.1249722
0.2010000	285.3029218	17.4455716	8093.277249	0.7158870	237.7524348
0.2410000	422.5012226	30.3993367	20923.68656	0.8439462	352.0843522
0.2820000	591.6716877	48.8518145	47211.16656	0.9709920	493.0597398
0.3210000	778.8999691	71.8364552	91687.41820	1.0881252	649.0833076
0.3610000	996.8455695	101.3707128	166268.7161	1.2047232	830.7046413

Table 4. "The Variation of Flow Variables in Propagating Cylindrical Strong Shockwaves".

$U/a_0 = 20, \quad \lambda = 1, \quad \rho' = 1.5, \quad p' = 14.1581, \quad \gamma = 1.4$
 $D = 0.6678675, \quad B = -4.5066661, \quad E = 0.6678675, \quad \text{and} \quad C = -2.0160001$

R	U	U/a ₀	P	P	U
$\Omega_0^2 = 1.5, \quad k_1 = 1.14, \quad k_s = 1.0693744^*$					
0.1613159	159.9250379	9.7371365	2076.465729	0.5845536	133.0270865
0.2010000	258.4372453	19.2254003	6640.827296	0.7158870	215.3643711
0.2410000	382.7162344	34.0142387	17096.39474	0.8439462	318.9301953
0.2820000	535.9567203	53.6375335	38738.48188	0.9709920	446.6306000
0.3210000	705.5546033	78.6667110	75232.87027	1.0881252	587.9621694
0.3610000	902.9773010	110.639578	136429.5490	1.2047232	752.4810842
$\Omega_0^2 = 2.0, \quad k_1 = 0.8, \quad k_s = 7.5126629^*$					
0.1613159	134.0442564	11.6029251	1458.774834	0.5845536	111.7035470
0.2010000	216.6142245	22.8615175	4665.368193	0.7158870	180.5118538
0.2410000	320.7811318	39.6548833	12061.46043	0.8439462	267.3176098
0.2820000	449.2226927	63.3221221	27214.88658	0.9709920	374.3522439
0.3210000	591.3745303	92.3970456	52853.23861	1.0881252	492.8121086
0.3610000	756.8428888	129.118248	95845.65820	1.2047232	630.7069073

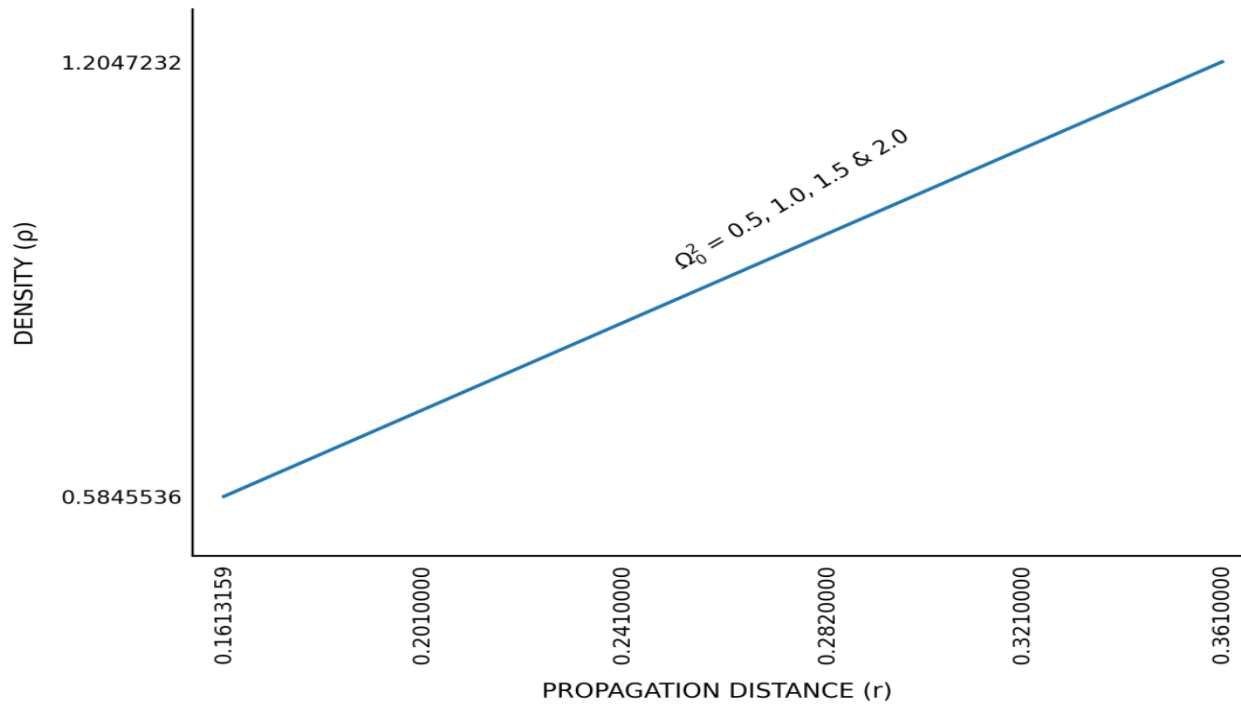


Fig 1. Variation of the density immediately behind the shock with the propagation distance (r) and Ω_0^2 .

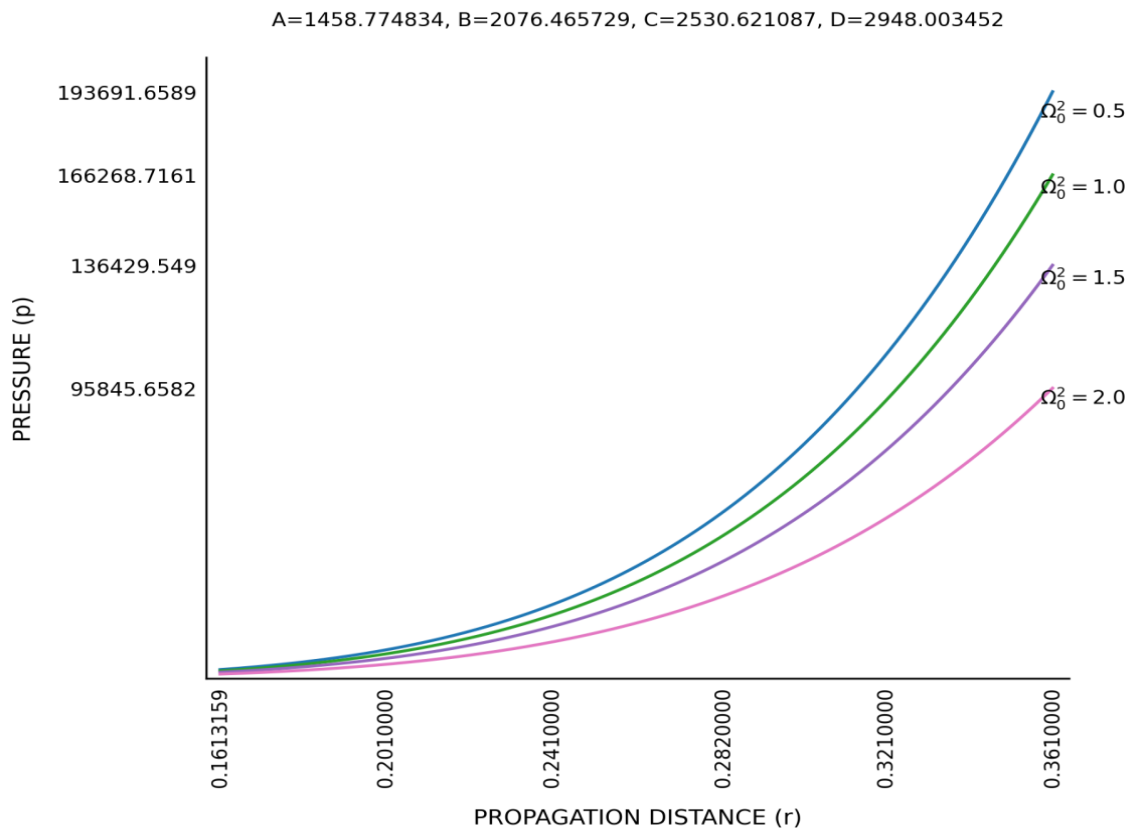


Fig 2. Variation of the pressure immediately behind the shock with the propagation distance (r) and Ω_0^2 .

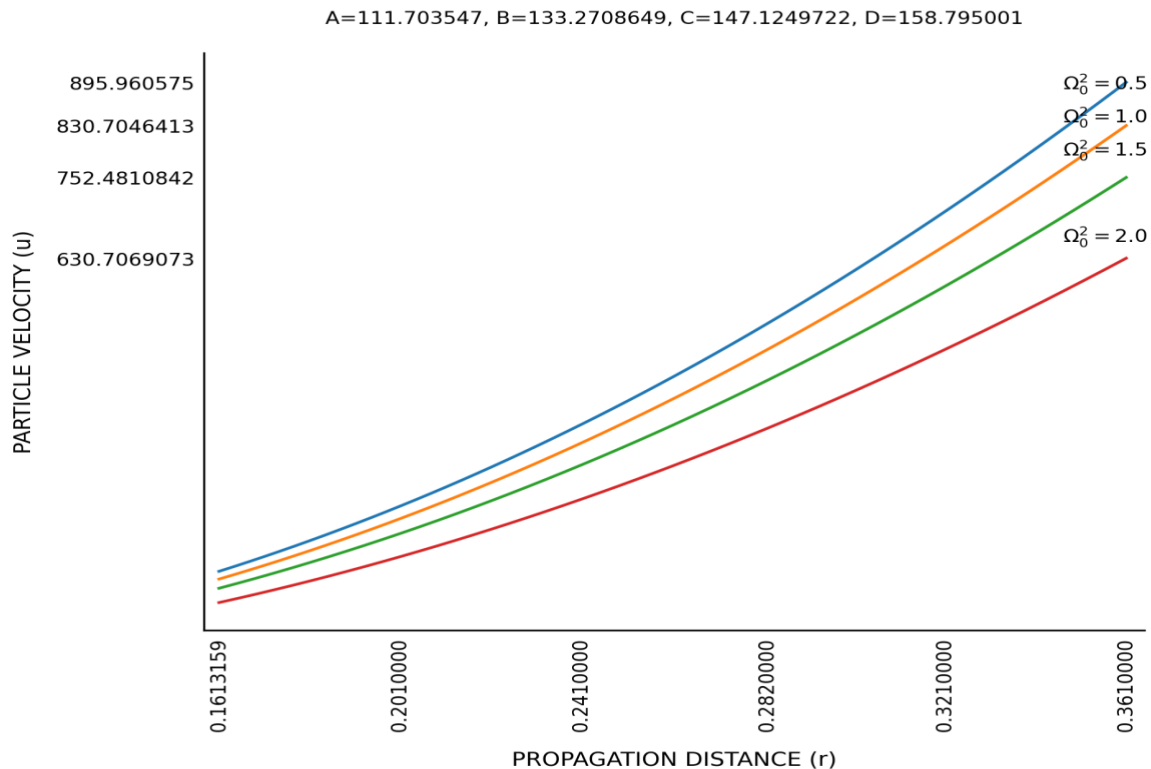


Fig 3. Variation of the particle velocity immediately behind the shock with propagation distance(r) and Ω_0^2 .

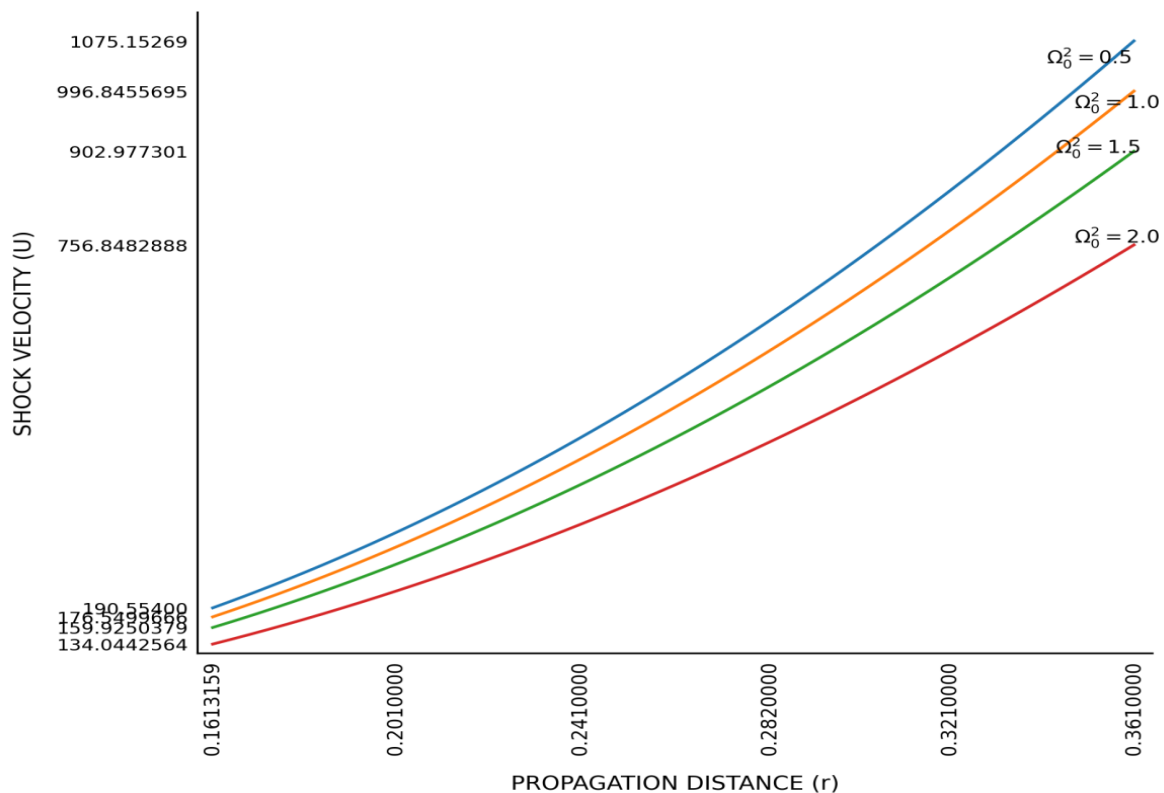


Fig 4. Variation of the shock velocity immediately behind the shock with propagation distance (r) and Ω_0^2 .

Result and Discussion:

Taking $U/a_0 = 20$ at $r = 0.125$ and $\Omega_0^2 = 0.5$, the flow variables given by the expressions have been computed numerically. The shock front locations are given in Tables [1] and shown in graphs near approximately 0.1613159 i.e., the root permitted by the entropy distribution condition. The deviations from this condition for the distances chosen for computation are given in Table [2,3] and shown in graphs.

(a) Density: The variation of density immediately behind the shock with propagation distance r for different values of Ω_0^2 . It is observed that the density behind the shock increases with increasing propagation distance. The variation is nearly linear over the range considered, indicating a progressive increase in the post-shock density as the shock propagates outward. The parameter Ω_0^2 also affects the density distribution, demonstrating the influence of the corresponding physical effect on the propagation characteristics of the shock (Fig.1).

(b) Shock velocity: The variation of shock velocity U with propagation distance r for different values of Ω_0^2 . It is observed that the shock velocity increases continuously with the propagation distance for all considered values of Ω_0^2 , indicating acceleration of the shock during propagation. For a fixed value of r , the shock velocity decreases with increasing Ω_0^2 . The curve corresponding to $\Omega_0^2 = 0.5$ exhibits the highest shock velocity, whereas the curve for $\Omega_0^2 = 2.0$ gives the lowest velocity. The separation between the curves increases with propagation distance, showing that the effect of Ω_0^2 becomes more pronounced as the shock propagates. Thus, Ω_0^2 has a decelerating or retarding influence on the shock velocity (Fig 2).

(c) Pressure: Depicts the variation of pressure immediately behind the shock with propagation distance for different values of Ω_0^2 . It is observed that the pressure increases continuously with the propagation distance for all considered values of Ω_0^2 . The pressure initially varies slowly and subsequently increases more rapidly as the shock propagates. For a fixed propagation distance, the pressure decreases with an increase in Ω_0^2 . The maximum pressure is obtained for $\Omega_0^2 = 0.5$, whereas the minimum pressure corresponds to $\Omega_0^2 = 2.0$. The increasing separation between the curves at larger propagation distances indicates that the effect of Ω_0^2 becomes more pronounced during shock propagation. Thus, the parameter Ω_0^2 has a retarding influence on both the shock velocity and the pressure immediately behind the shock (Fig.3).

(d) Particle velocity: The variation of particle velocity immediately behind the shock with propagation distance for different values of Ω_0^2 . It is observed that the particle velocity increases continuously with the propagation distance for all values of Ω_0^2 . The rate of increase becomes more pronounced at larger propagation distances. For a fixed propagation distance, the particle velocity decreases with increasing Ω_0^2 . The maximum particle velocity is obtained for $\Omega_0^2 = 0.5$, while the minimum corresponds to $\Omega_0^2 = 2.0$. The increasing separation between the curves indicates that the influence of Ω_0^2 becomes more significant as the shock propagates. Thus, an increase in Ω_0^2 has a retarding effect on the particle velocity immediately behind the shock (Fig 4).

These present results are in agreement with earlier work.

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